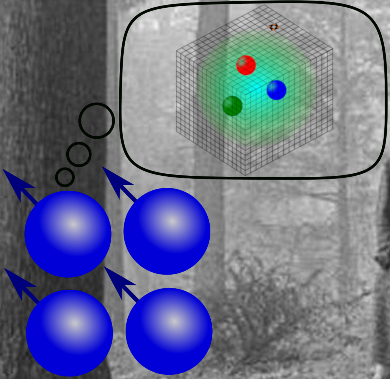
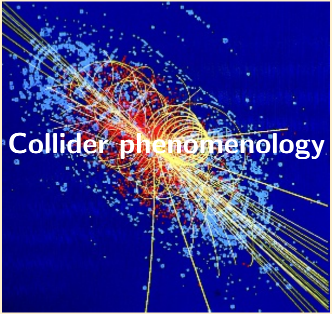
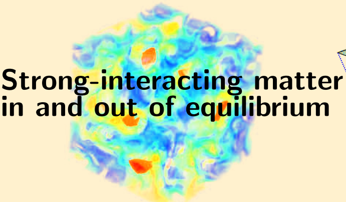
Quantum Algorithms for HEP

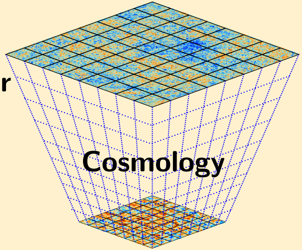
Hank Lamm

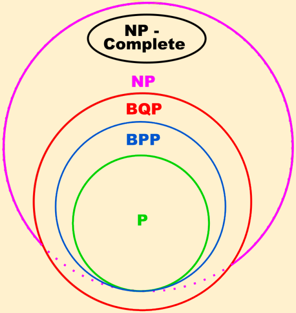


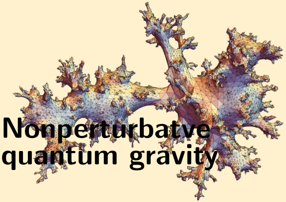
Fundamentally, HEP requires QC[1]







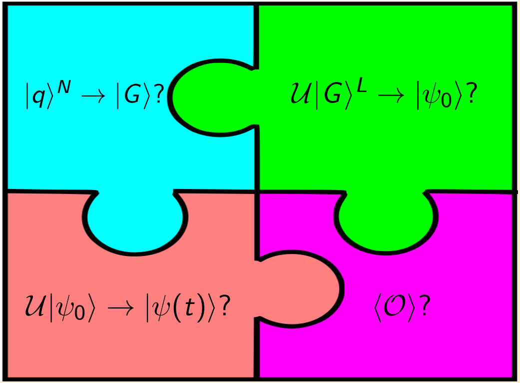




[1] Bauer, C. W. et al. In: (Apr. 2022). arXiv: 2204.03381 [quant-ph].

What “champagne problems” need to be solved?

- **Encoding**: How are bosons represented as registers?
- **Initalize**: How can registers be set to a state?
- **Propagate**: How can gates evolve states?
- **Evaluate**: How can observables be computed?



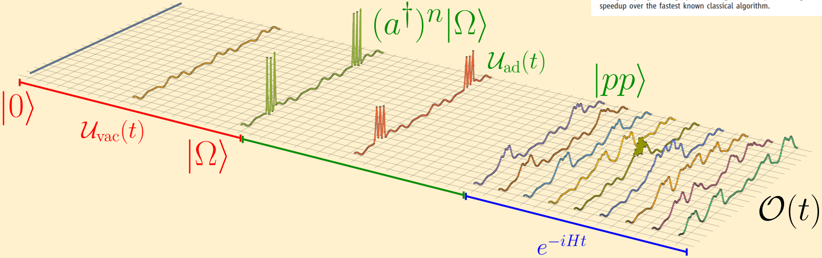
- **Mitigate**: Can LFT-specific QEC/QEM be cheaply designed?

What might a galactic algorithm look like?

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1*] Keith S. M. Lee,[2] John Preskill[3]

Quantum field theory reconciles quantum mechanics and special relativity, and plays a central role in many areas of physics. We developed a quantum algorithm to compute relativistic scattering probabilities in a massive quantum field theory with quartic self-interactions (ϕ^4 theory) in spacetime of four and fewer dimensions. Its run time is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. In the strong-coupling and high-precision regimes, our quantum algorithm achieves exponential speedup over the fastest known classical algorithm.



Vacuum Prep+**Adiabatic evolution**+**Trotterization**+Measurements[2]

Example: $|\langle p\bar{p}|U(t)|\pi\pi\pi\pi\rangle|^2$ needs $\mathcal{O}(10^8)$ **logical qubits**

$\approx \left(\frac{4\text{ fm}}{0.05\text{ fm}}\right)^3 \times (3\text{ links} \times 11\text{ qubits} + 3\text{ colors} \times 2\text{ flavors} \times 2\text{ spins} \times 1\text{ qubit})$

[2] Jordan, S. P., K. S. M. Lee, and J. Preskill. In: *Science* 336 (2012). arXiv: 1111.3633 [quant-ph].

Today's estimate: $\mathcal{O}(10^8)$ q & $\mathcal{O}(10^{55})$ T-gates[3]

"...99.998% of the gate counts stem from **QFOPs**...The SU(3) *HI collision* problem is...> 3 **yrs** of runtime on an **exa-scale** quantum supercomputer."

- *pp* scattering on $(L/a)^d = 100^3$ lattice
  - Observables dictate L/a, T/a_t, $d \implies$ **fewer** qubits
- **Kogut-Susskind** Hamiltonian
  - Improved Hamiltonians will increase $a \implies$ **fewer** qubits
- Truncate to $\Lambda = 10$ in the electric field values **(24q)**
  - Better truncations allow **fewer** qubits per link near continuum

[3] Kan, A. and Y. Nam. In: *arXiv preprint arXiv:2107.12769* (2021).

Today's estimate: $\mathcal{O}(10^8)$ q & $\mathcal{O}(10^{55})$ T-gates[4]

"...99.998% of the gate counts stem from **QFOPs**...The SU(3) *HI collision* problem is...> 3 **yrs** of runtime on an **exa-scale** quantum supercomputer."

- **Trotterization** $\mathcal{U}(T)$ with **loose** error bound $\epsilon_{Trotter}$
  - Other methods: variational, QDRIFT, qubitization ...
- **Decomposing specific** unitaries into gates introduces $\epsilon_{synthesis}$
  - Different **platforms**: Analog, Digital, CV, Qudits
- $\epsilon \equiv \epsilon_{Trotter} + \epsilon_{synthesis} = 10^{-8}$
  - Current theoretical errors can be $\mathcal{O}(1)$

Cracking RSA and Quantum Chemistry need $\mathcal{O}(10^7)$ q & $\mathcal{O}(10^{20})$!

[4] Kan, A. and Y. Nam. In: *arXiv preprint arXiv:2107.12769* (2021).

Perhaps THE question of the next 10 years

Can **NISQ**[5] era give **practical quantum advantage?**[6]

YES: What are they, so we[7] can focusing on them more!

- Identify **target** calculations
- Resource **estimates** & Dedicated HEP devices?
- **Error mitigation**
- **NISQ** algorithms

NO: We[6] shouldn't devote as much time to some topics.

- Emphasize **theoretical developments** over running today
- **HEP-specialized** Hardware
- **Error Correction**
- Quantum **Stack** & **FT** algorithms

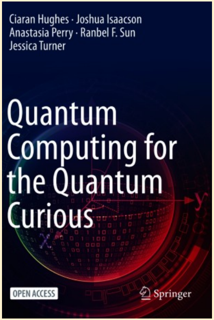
[5] Nebulously defined as $O(10^{2-4})$ qubits/layers without error correction

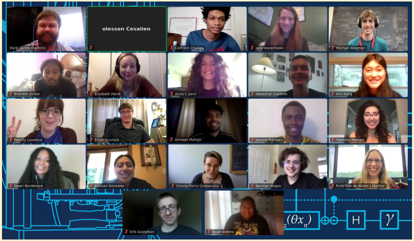
[6] Nebulously defined as some *new* physics insight that couldn't *reasonably* be gotten classically

[7] HEP physicists

Developing quantum-ready physicists

- **WE** get to define **US**
- Requires **diverse and inclusive** workforce with skills **beyond** traditional HEP.
- Opportunities exist as early as **high school**.
- Portfolio of funding mechanisms, career paths and mentoring **needed**.
- **QCIPU** just finished year 2. Perhaps **QuTASI**? **Hackathons**?





It's one calculation, what could it cost?

A lot has been solved...and lots more to do

- Digitizing Field Theory
- Formulating **state preparation**
- Performing **Time Evolution**
- **Measurements and Observables**
- HEP-specialized **QEC/QEM**

The next 10 years will seem many leaps in our understanding of quantum sims of HEP, and will someday open new avenues